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A Test Rig for Thermal Analysis of Heat Sinks for Power Electronic Applications

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***Abstract*—This paper discusses the design and manufacture of a test rig for practical thermal analysis of the temperature distribution across forced air-cooled heat sinks. High-temperature gradients across power electronic modules that have a large area of semiconductor structure can result in premature failure of the components due to mechanical stress-related fatigue. Computer modelling and simulations predict the temperature distribution across the heat sink, but physical temperature measurements are required to validate these results. In order to acquire these temperature readings, a bespoke test rig is designed and manufactured. Temperature readings obtained using this test rig are applied for comparison to those obtained by computer simulation and, hence provide validation of the computer simulation results.**

Keywords*—*temperature gradient, power electronic module, IGBT, power semiconductor reliability, forced air heat sink

I. INTRODUCTION

The lifetime and reliability of power semiconductors significantly impact the reliable operation of industrial systems and domestic applications where power electronic devices are integrated as a core component [1]. Yang et al. [2] reported that 31% of all component failures in power converters are related to semiconductor faults whereas 55% of IGBTs are failed due to the temperature impact [3]. Therefore, the thermal analysis of the power devices attracts much attention in order to improve the semiconductor thermal management and extend understanding of its thermal behaviour [4]-[6].

Apart from ambient temperature, the power loss in semiconductors associated with the load variation (mission profile) mainly affects its thermal stress and junction temperature. A very hazardous factor leading to the semiconductor failure is the temperature gradient of the structure. It has occurred in situations where there is an uneven distribution of heat which generates thermo-mechanical stress produced as a result of the combined use of different materials having different coefficients of thermal expansion. The service life of a semiconductor component is strongly dependent on the level of the temperature gradient, as high-temperature differences inside the component lead to accelerated ageing. [7]-[9].

In order to meet the aspect of sustainability and to ensure a longer lifetime, it is desirable to reduce this gradient to a minimum. The method most commonly used for thermal management resorts to the use of heat sinks on which the semiconductor devices are mounted. Heat sinks are the most common, and comparatively the cheapest, way of cooling components to reduce the temperature of the junction in the semiconductor and of the entire component. To generate the best possible cooling, a fan is also used. Depending on the type of mounting, this fan generates an air flow through the cooling fins, resulting in a temperature difference over the length of the heat sink [10].

Fig. 1 illustrates a typical problem of thermal gradient that occurred in the temperature distribution across the heat sink applied for air forced cooling of the power electronic inverter. The cooling system of a three-phase inverter usually consists of three power electronic modules installed in a row on the surface of the heat sink. The module located close to the air inlet has the lowest temperature whereas the device at the outlet is hottest. The contours of the thermal distribution of such a system are shown in Fig. 1a. An example of the thermal gradient development is shown in Fig. 1b where the red line is the temperature variation along the middle line of the heat sink top surface and the blue line is the temperature increase of air flowing through fins from the heat sink inlet to the outlet.

If it is assumed that all components of a system are equally responsible for its function, the component that is exposed to the greatest thermal load determines the system's runtime. The goal in developing a system that includes power components is therefore to keep the temperature gradient of the components as evenly distributed as possible. This can be done by mechanically modifying the heat sink [10]-[12] or by so-called active thermal control [13],[14]. The latter requires the use of sensors and control technology to measure the temperature of the semiconductor component and to regulate the control of the fan as well as the control of the component.

Following some attempts to build test setups for practical investigation of thermal stress in power

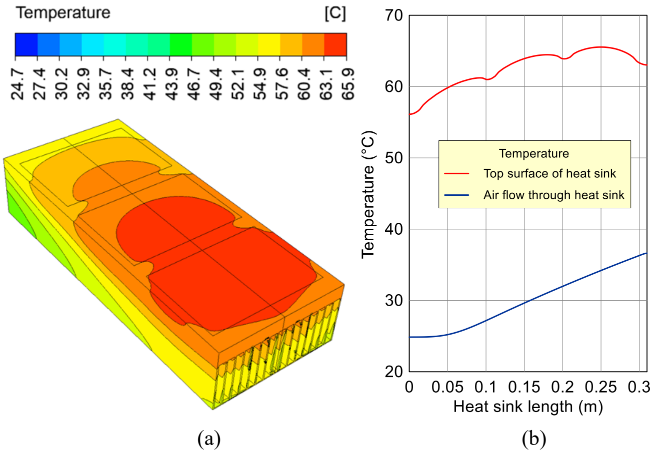

Fig. 1. Illustration of a typical problem of thermal gradient in the temperature distribution across the heat sink applied for air forced cooling of power electronic inverter, (a) contours of the thermal distribution; (b) temperature variation on the surface of the heat sink and air flow temperature increase [7].

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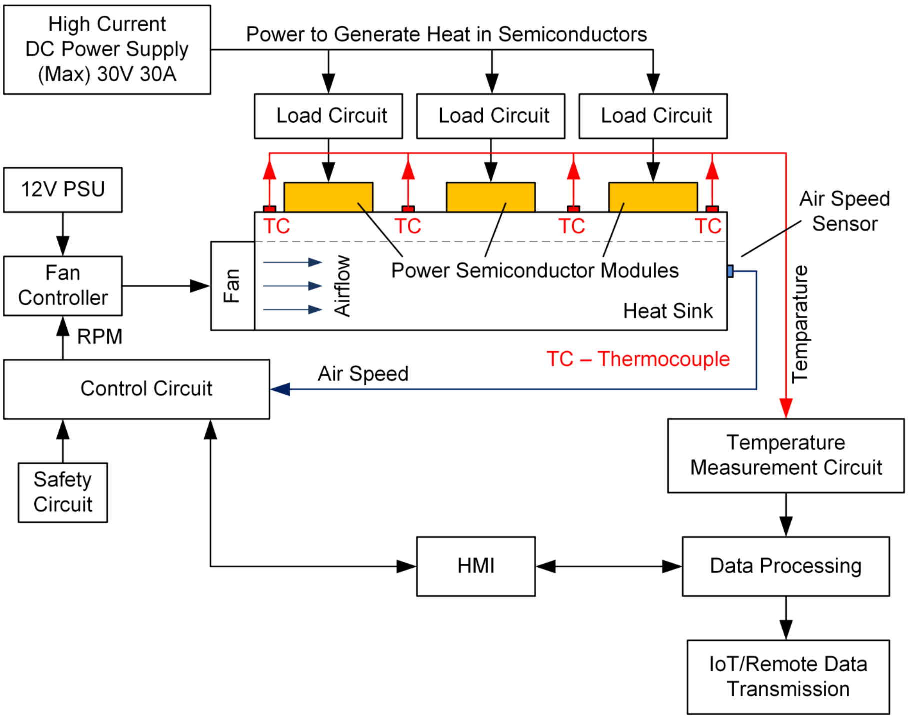

Fig. 2. Schematic block diagram of the test rig.

semiconductors [15]-[17], this paper provides a discussion on the development details of a test setup for determining the temperature gradient of semiconductor components. The test subject is three identical power transistors (IGBTs) mounted on a forced air cooled heat sink.

II. Test Rig Design

Fig. 2 shows a schematic block diagram of the test rig. The main object under test of the test rig is the heat sink having three (or six) power semiconductor modules installed on the top surface in one row. The type of heat sink used for the analysis and practical investigation is considered a standard device widely implemented in the power electronic industry. The fan (or set of fans) producing forced air flow through the heat sink fins is controlled to adjust the required air speed and therefore required conditions for heat transfer from the fins' surface to the ambient. The air speed for standard heat sinks is usually dictated by the manufacturers to provide expected thermal resistance. The air speed is adjusted and stabilised using a closed loop controller processing the feedback signal from the air speed sensor attached to the heat sink outlet.

The top surface of the heat sink is equipped with a set of thermocouples to obtain readings of temperature in different places. The location of the thermocouple depends on the type and size of the heat sink and is selected to provide temperature readings corresponding to the thermal map produced as a result of thermal modelling and simulation. Therefore, the test rig temperature measurement is designed in a manner to validate the numerical results.

The voltages from the thermocouples representing temperature readings are processed using a temperature measurement circuit and following a data processor. The data processor unit is filtering, collecting and transmitting the temperature readings to cloud storage for further data processing, analyses and visualisation on an external or remote screen. Taking into account the air temperature this approach can provide detailed readings of a transient of the thermal gradient development based on practical results obtained from the test.

Following industrial safety requirements, the test rig is also equipped with a protection system to prevent unauthorised access into the cage considered a safety area (safety cage).

Fig. 3 demonstrates the front view of the test rig hardware. It consists of the test cage (safety cage) and the compartment for control and automation circuitry installation. The test cage is not thermally isolated and provides air convection with the ambient. The cage area is covered by a combination of transparent plastic panels at the front door/top side/back side and a wire net at each side as shown in Fig. 4.

To ensure that access to the inside of the enclosure is as restrictive as possible, a keypad is installed on the left side of the cage (Fig. 4). This allows a previously set combination of numbers to be entered and thus a magnetic lock to be switched, which opens the front door. The magnetic lock is installed in the upper-right corner of the front door. It is energised in case to prevent opening the cage door.

To better monitor the temperature and humidity inside the safety cage, a digital humidity and temperature (DHT) sensor is attached to the upper mounting rail. In combination with a microcontroller, this allows to check whether there is a risk of Electrostatic Discharge (ESD) due to low humidity. This measure is part of the ESD safety concept of the system.

Fig. 5 shows the assembly of the control and automation circuitry to load power semiconductors, control air flow through the heat sink, collect and process reading data.

III. Power Semiconductor Loading

Through the designed control system, the current flow through the power electronics was designed in the form of a current source. This enabled the heat development to be

Fig. 3. Front view of the test rig.

Fig. 4. Side view of the test rig.

adjusted in a controlled manner, thus generating desired levels of power losses. The transistors of power semiconductor modules are controlled with different continuous input parameters to obtain a comparison with the numerical simulations.

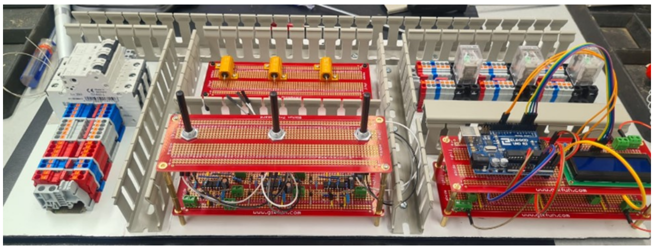

Fig. 5. Control and automation circuitry assembly.

The majority of power electronic modules applied for electric drive inverters are based on IGBT transistors. These devices have been selected as an object for emulation of power loss using a dc current source controller. Usually, the power loss in a semiconductor device operating as a three-phase inverter component is generated in the IGBT transistor and flywheel diode. However, for this test rig, the current source controller produces dc current which loads the IGBT transistor only. Some sources reported [18] that power IGBTs are not operating reliably in the linear mode under static conditions because it is primarily designed for switching mode of operation. This is why the voltage drop across IGBTs in the linear mode was selected at lower level, about 10V. The external regulated power supply having a load capability of 30A at 30V of the output voltage is implemented to energise IGBT power modules installed on the heat sink. Using this power supply, the test rig can provide a practical test of three power semiconductors to load each device at 100W max. In the case of IGBTs, the rating current is 10A through each device at a voltage drop of 10V.

Fig. 6 shows a circuit of a controller to load a single transistor IGBT module or one IGBT of a multi-transistor module. It is based on the principle of a current source where the value of the current through the IGBT is installed by a potentiometer manually or by input from the main control circuit. The power loss in the IGBT can be calculated as the multiplication of installed current through the transistor and the voltage drop across collector and emitter terminals.

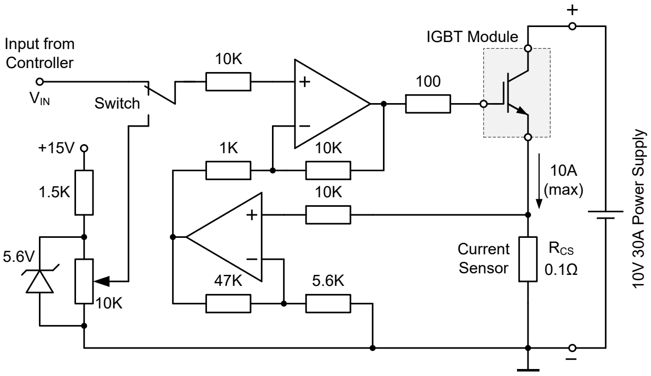

Fig. 6. The circuit of the controller to load of single-transistor IGBT module

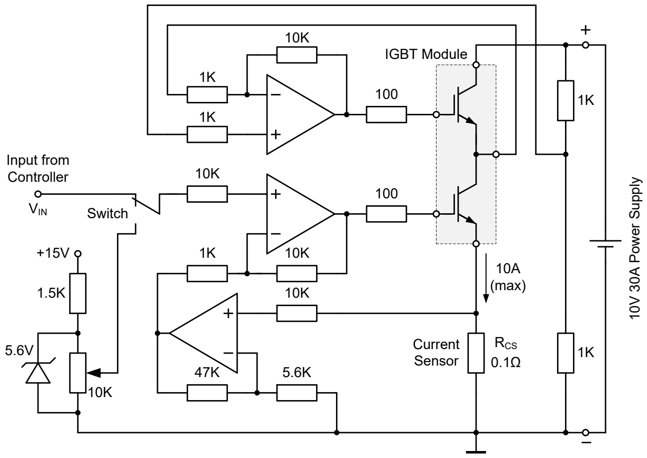

Fig. 7. Circuit diagram of the controller to load both IGBT transistors in the power semiconductor module.

In the case of a multi-transistor power module, it is required to energise two IGBTs connected in series as shown in Fig. 7. This circuit equally distributes power loss between two transistors by providing the same voltage drop across each IGBT. Double IGBT current source circuit can also operate manually or under control of the main controller.

IV. CONCLUSION

The outcome of this hardware design has successfully achieved its aim of developing a test rig for practical thermal investigation of various heat sinks. The test rig provides temperature measurement of the heat sink surface in the range of 0°C to 120°C. It is designed to ensure the temperature measurement data to be collected that will significantly contribute to the understanding of temperature gradients across heat sinks. The final assembly of the proposed test rig allows for measurement flexibility to accommodate different power semiconductor devices, different profiles and types of the heat sink and various air flow parameters. The decision to use thermocouples as the temperature sensing method was informed by their accuracy, moderate cost, and minimal influence on the cooling capacity of the heat sink. The designed temperature measurement circuit was thoroughly tested for signal integrity and power consumption. The results showed that it met the required performance criteria and ensured functionality in noisy environments.

The insights gained from the temperature gradient measurements will facilitate the development of improved heat sink designs that minimise temperature gradients and the associated problems, ultimately extending the lifespan and reliability of these high power electronic systems.

A key objective of the project was to ensure upgradability for future work, enabling the integration of additional sensors as needed. The accompanying software effectively utilised commonly available libraries, contributing to the overall functionality of the software and successful implementation. The software also offers various settings and error handling, enhancing the systems' overall performance and allowing the gathering of additional valuable information. The temperature verification results highlighted the accuracy and precision of the temperature measurement circuit and the thermocouples, exceeding the projects' accuracy aim of ±0.8°C across the temperature range 20°C to 100°C, with a maximum absolute error of −0.265°C and +0.36°C.

The end goal being to obtain comparable readings between the two numerical and practical approaches. In that respect the project is still ongoing, and it is envisaged that further modifications and development will be required in terms of both temperature measurement and in controlling the airflow through the heat sink. The test rig has been designed in such a way that modifications to improve accuracy can be incorporated without major changes to the initial design. The budget for the project was £2500.

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